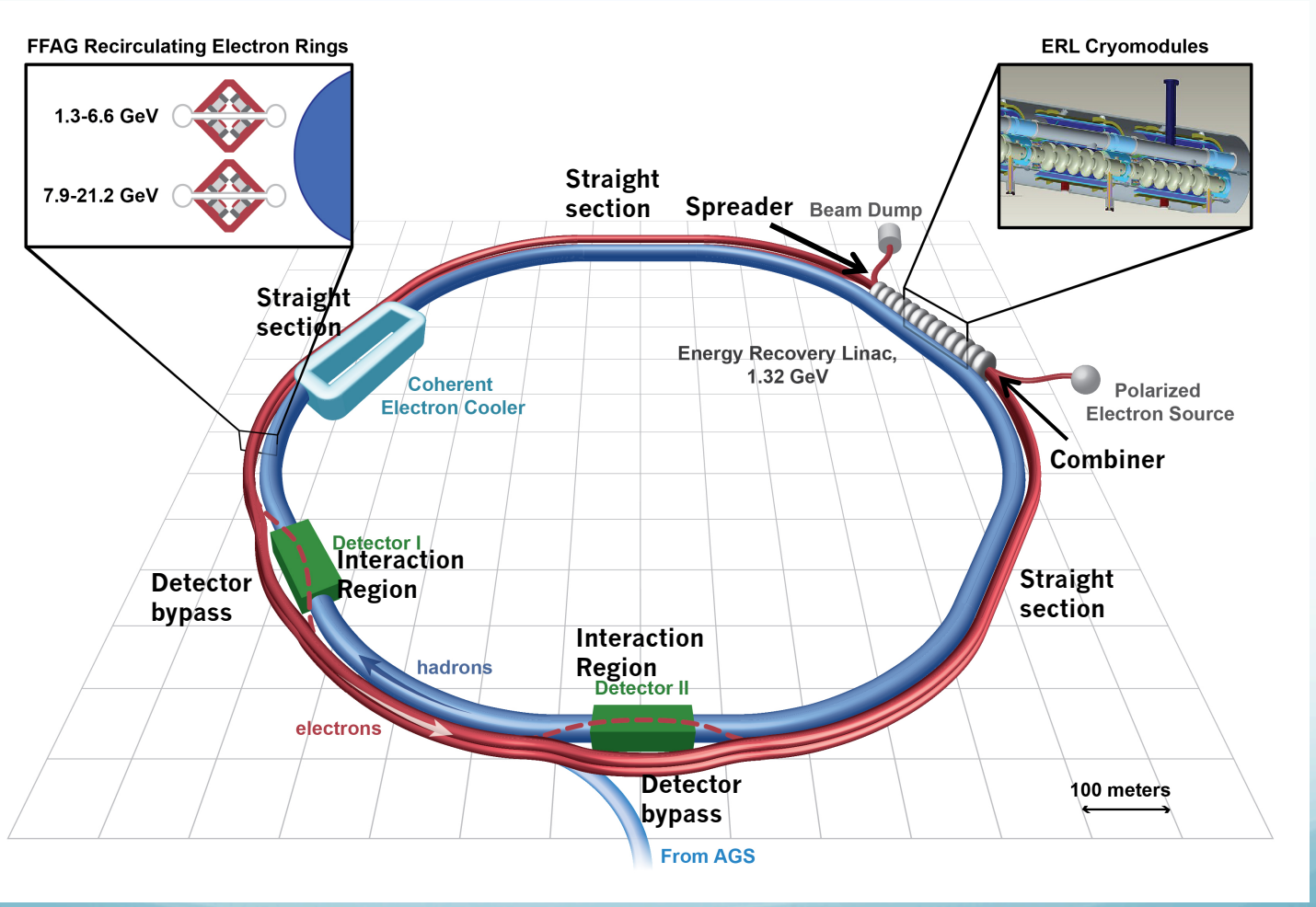
Beam and spin transport

V. Ptitsyn

eRHIC Electron Lattice Components



NS-FFAG approach for eRHIC

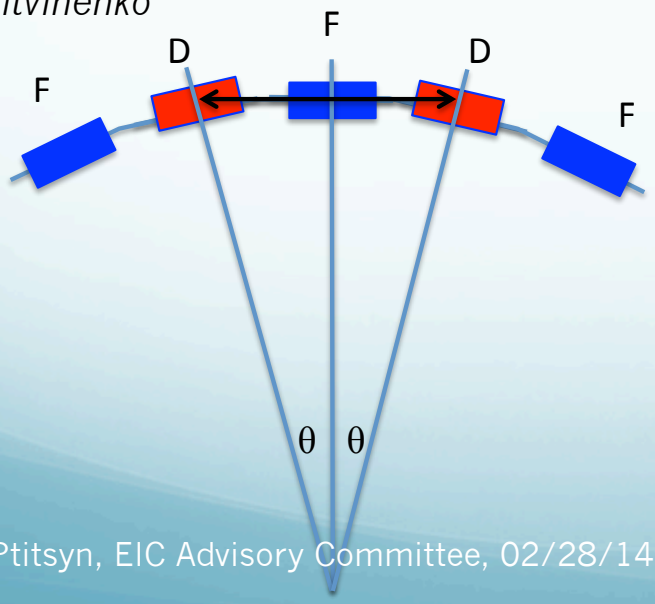
- Non-Scaling Fixed Field Alternating Gradient (NS-FFAG) approach is used for eRHIC recirculation passes.
- eRHIC FFAG cell is comprised of two quadrupoles (F & D) whose magnetic axes are shifted horizontally with respect to each other by an offset Δ .

  Strongly focusing, bent FODO cell

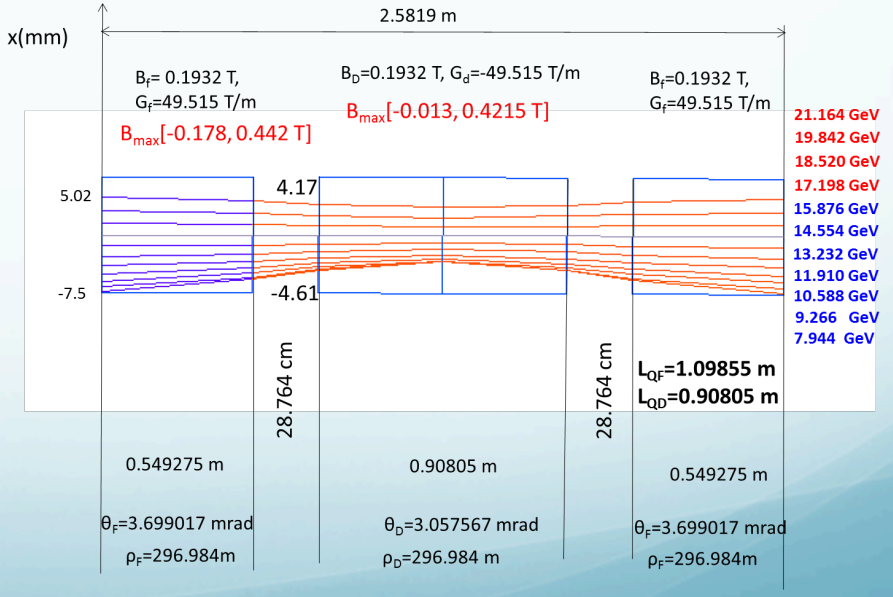
- Orbit and optics dependence on the energy can be accurately found in paraxial approximation

© V. Litvinenko

$$L=2(l_F+l_D+2d)$$



© D.Trbojevic



High energy FFAG cell

FFAG Recirculation passes

- Low energy FFAG: 5 recirculation passes; 1.34-6.62 GeV
- High energy FFAG: up to 11 recirculation passes; 7.94- 21.16 GeV
- Cell magnet design based on permanent magnet technology has been developed

Element	Length (m)	Angle (mrad)	Gradient (T/m)	Offset (mm)
All Drifts	0.288	0		
BD (Low)	0.908	3.058	9.986	-6.947
QF (Low)	1.099	3.699	-9.006	6.947
BD (High)	0.908	3.058	49.515	-3.901
QF (High)	1.099	3.699	-49.515	3.901

Cell parameters for both FFAGs

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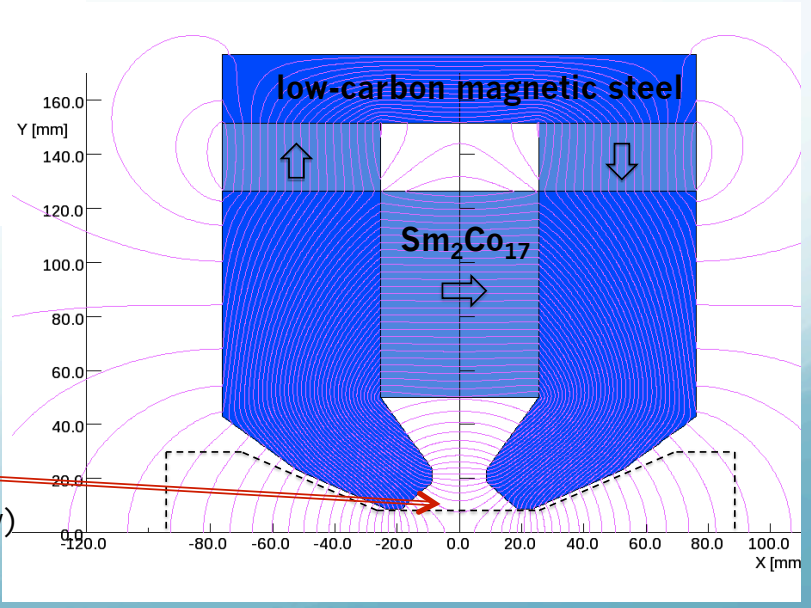
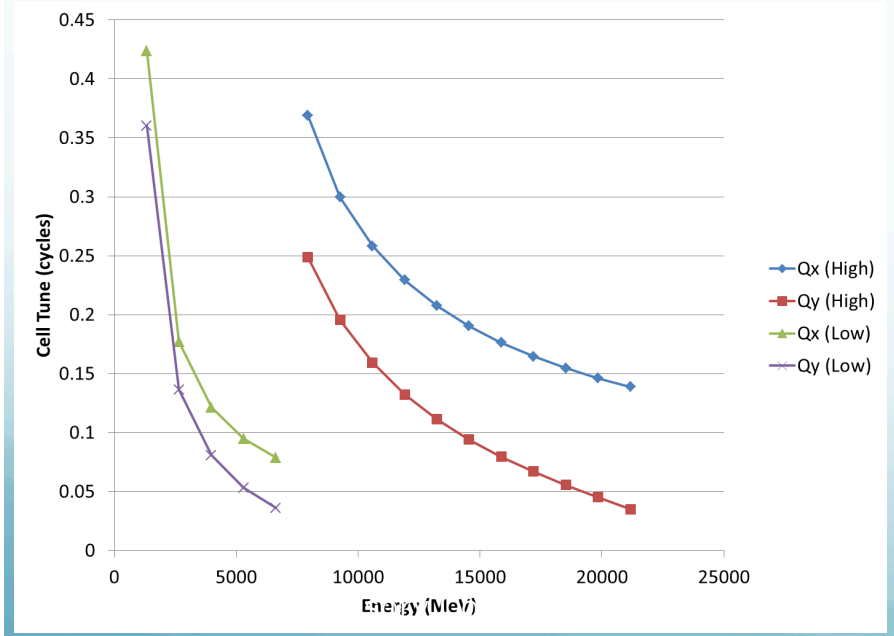


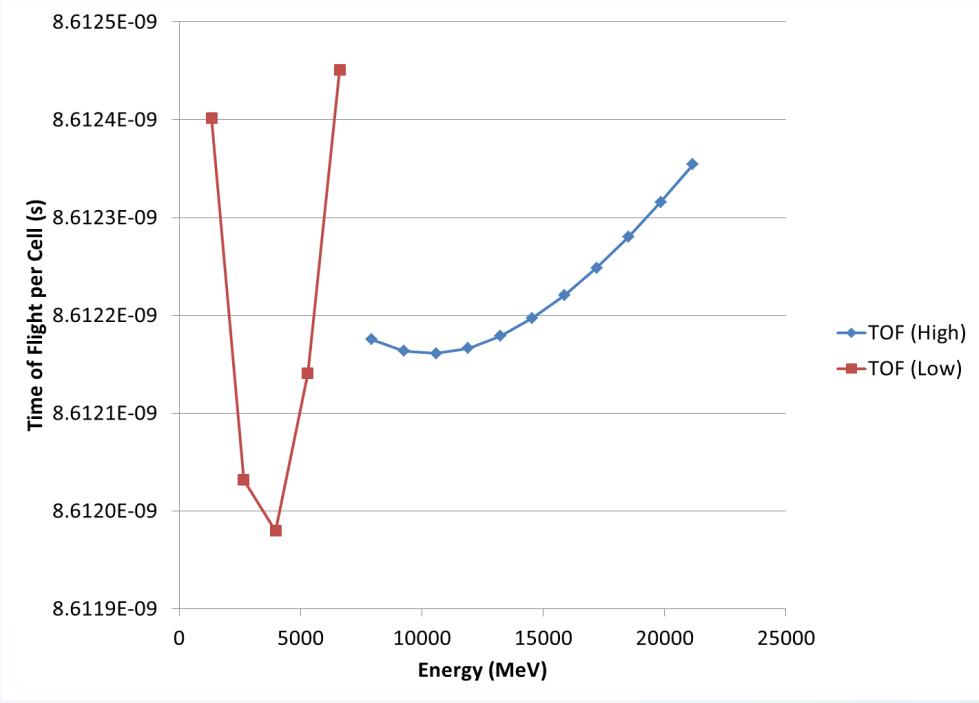
Correction coils location (dipole, quad, skew)

FFAG Cell Optimization

FFAG lattice optimization factors:

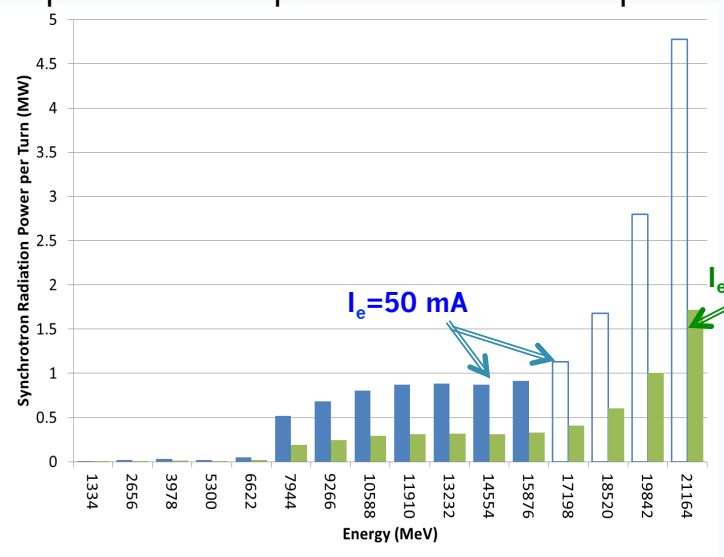
- energy acceptance;
- orbit spread;
- path-length spread;
- synchrotron radiation power





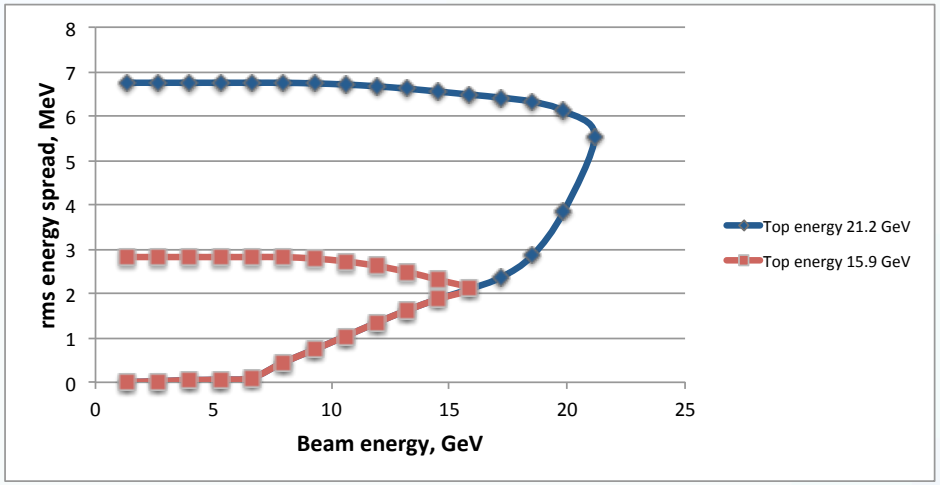
Synchrotron radiation effects

SR power loss per recirculation pass



Total SR power (arcs only) 10.2 MW:
operation at 15.9 GeV top energy -> 50 mA
operation at 21.2 GeV top energy -> 18 mA

Accumulated energy spread



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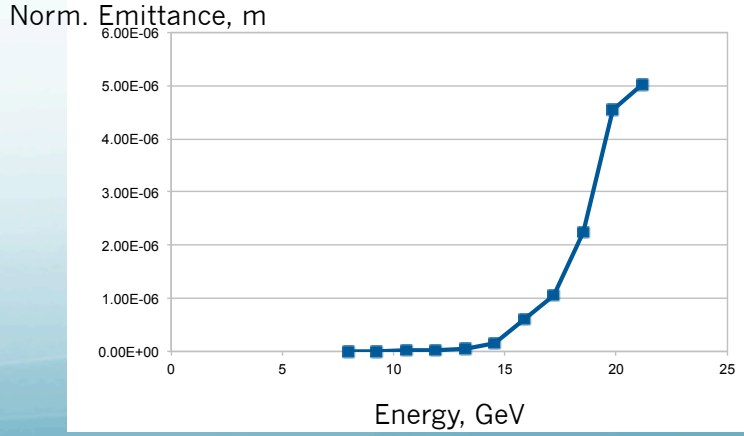
Transverse emittance growth



Energy loss compensation schemes under consideration:

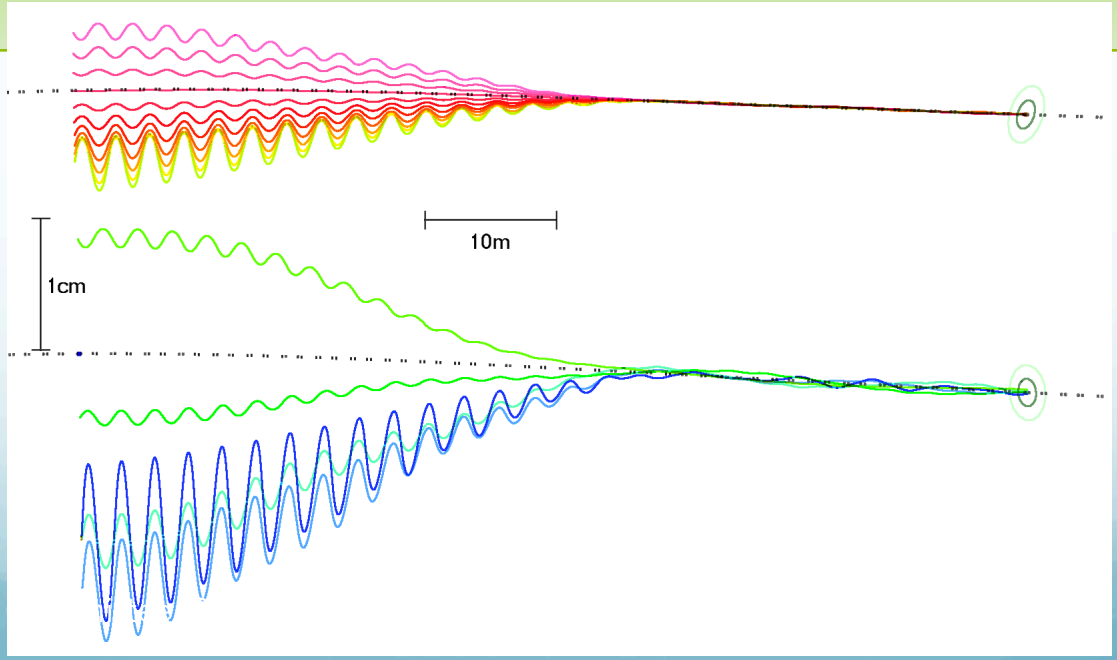
- 2nd harmonic (826 MHz) cavities
- Main linac RF phase offset + higher harmonic cavities

V. Ptitsyn, EIC Advisory Committee, 02/28/14

Straight section

- In straight sections of FFAGs all beam orbits follow same straight line trajectory
- The cell structure is similar to that of arcs, but with zero magnet offsets. No dipole field component on beam orbits.

- Matching section: merging the orbits from arcs to the the straight section trajectory is done by gradual (adiabatic) reduction of cell magnet offsets to zero. 17 cells.



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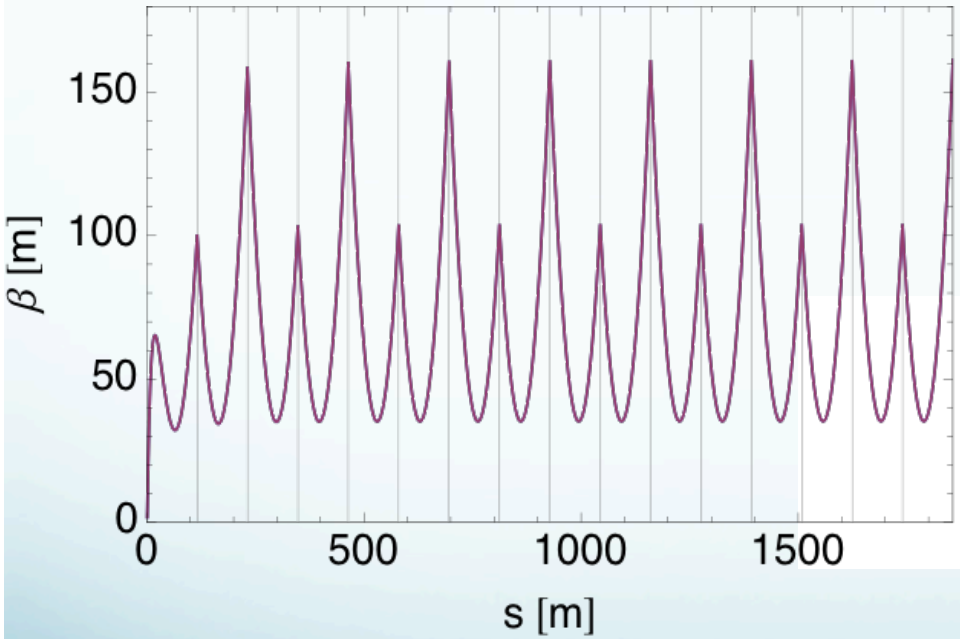
Linac Lattice

Linac: 120 m cold length; no quadrupoles inside

© *Y. Hao*



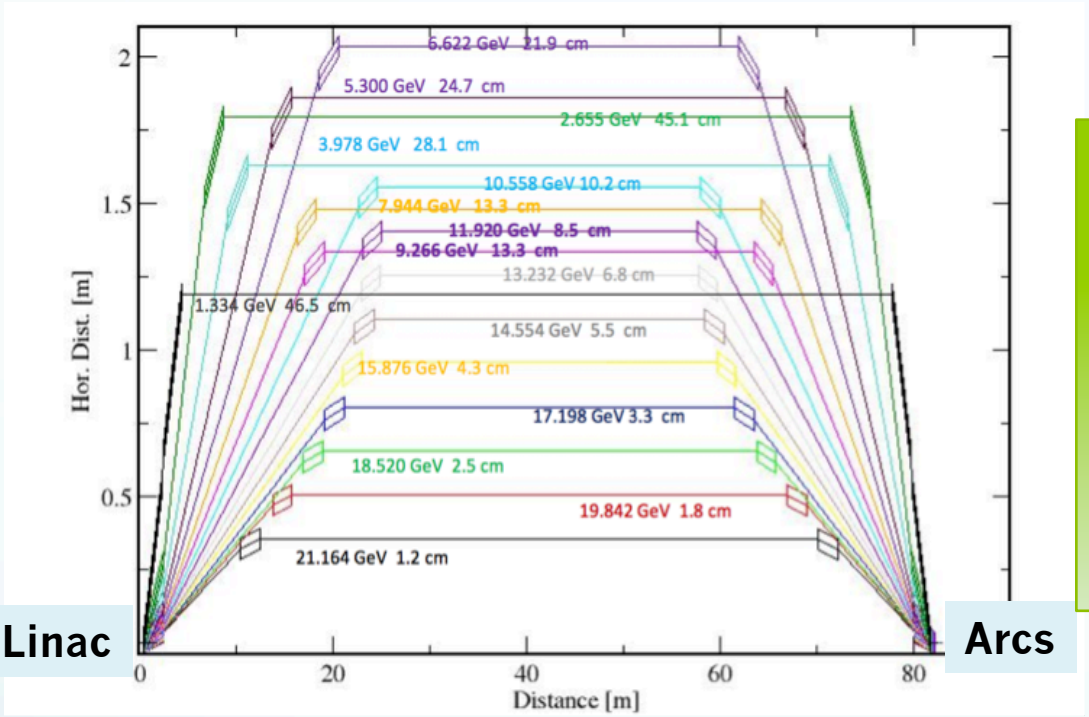
The beta function in the linac for 16 passes.
The horizontal and vertical optics are identical.
The grid lines separates the optics of each pass.

Multipass beam-breakup thresholds for 16 pass operation (simulation results)

Δf/f (rms)	Current Threshold (mA)
0	53
5e-4	95
1e-3	137
3e-2	225
1e-2	329

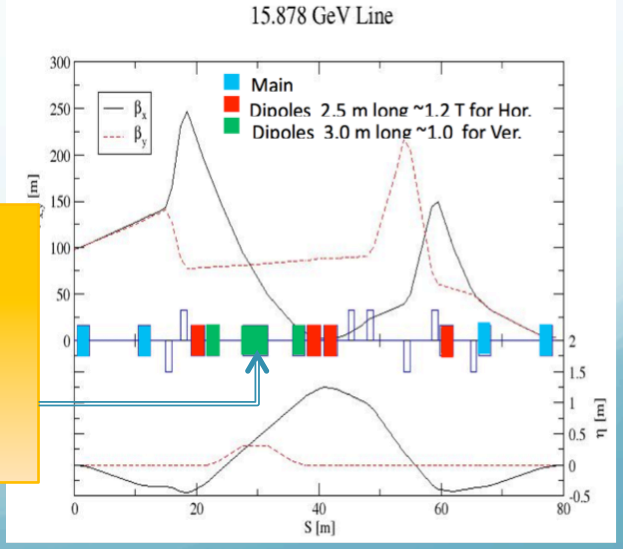
HOM frequency spread

Spreader and Combiner



© *N. Tsoupas*

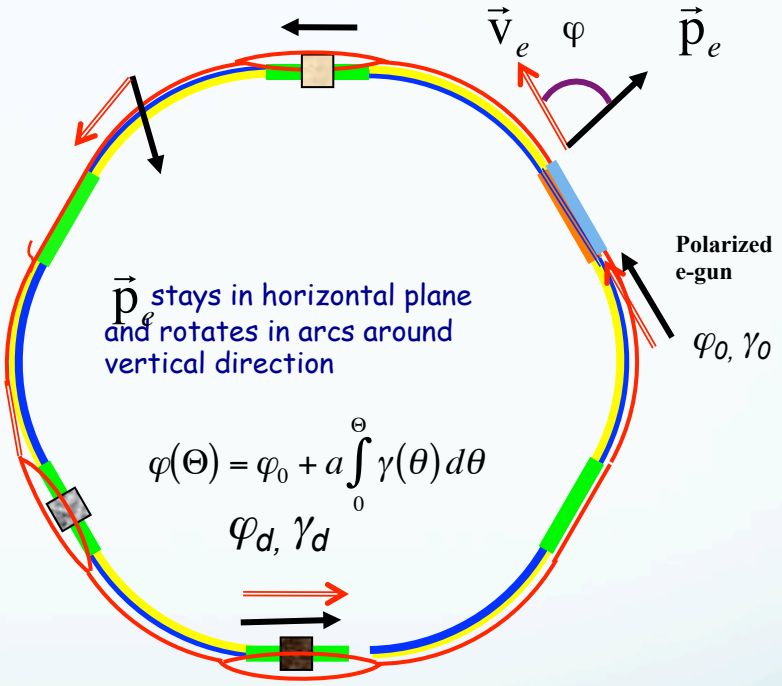
- Match optical function from the arc to the linac
- Ensure isochronous one turn transport:
  path length and R_{56} corrections
- Betatron phase advance adjusters

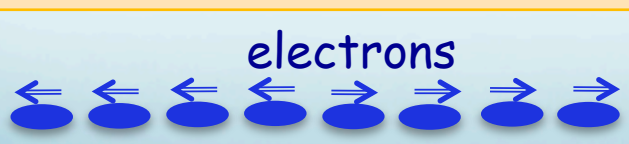


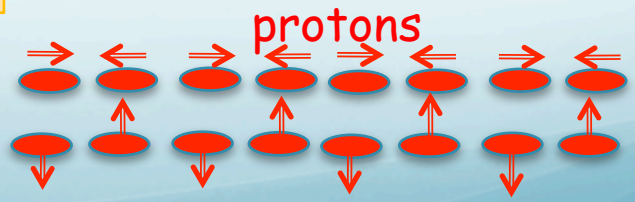
- 15 cm horizontal separation between individual lines
- Some of the lines are folded into the vertical plane to reduce path length difference
- Vertical magnet chicanes are used for pathlength correction

Electron polarization in eRHIC

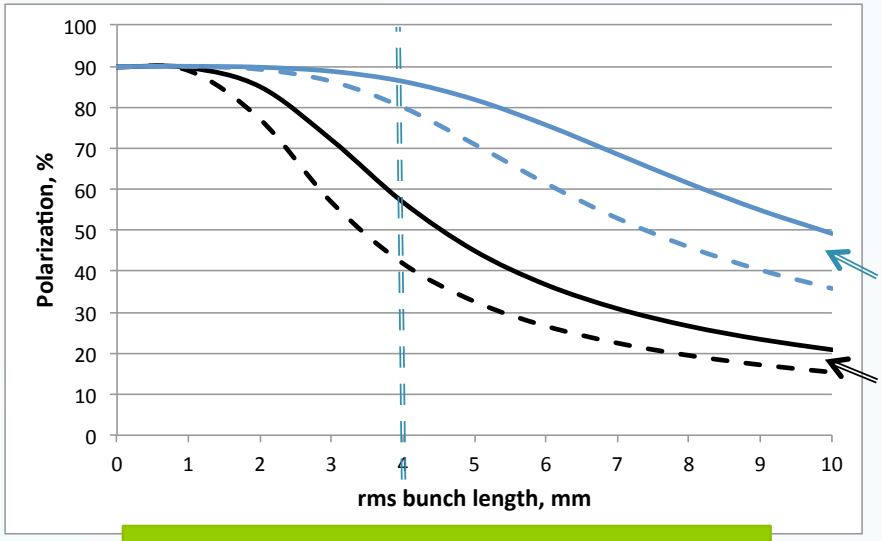
- 90% longitudinally polarized e-beam from DC gun with strained-layer super-lattice GaAs-photocathode with polarization sign reversal by changing helicity of laser photons.
- Only longitudinal polarization is needed in the IPs.
- eRHIC avoids lengthy spin rotator insertions. Cost saving.
- Integer number of 180-degrees spin rotations between gun and IPs
- With the linac energy of 1.322 GeV the polarization is longitudinal at both experimental IPs







Polarization preservation



De-coherence due to RF waveform

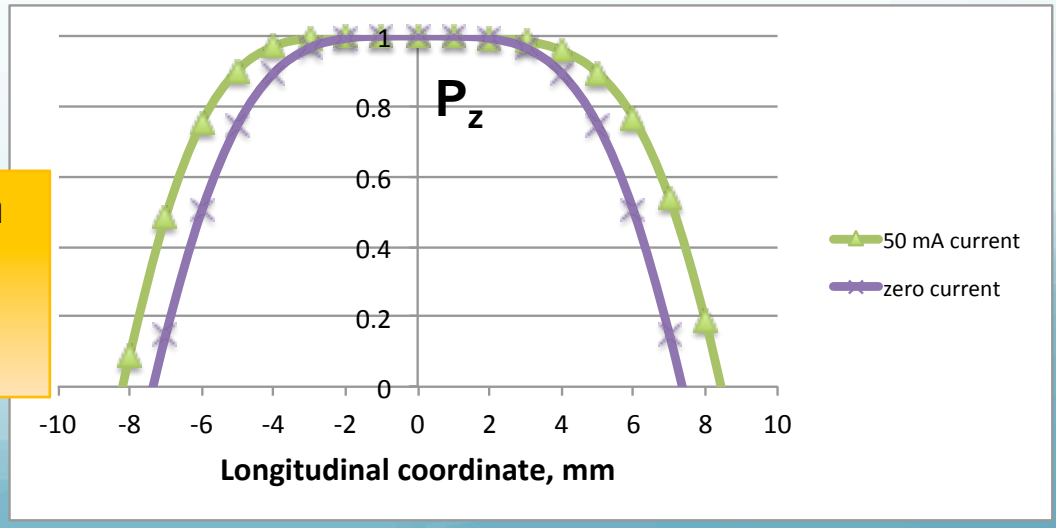
Shown is the averaged polarization: $P = \left\langle \cos\left(\Delta\varphi_{sp}\right) \right\rangle$

Dashed lines: 21.2 GeV
Solid lines: 15.9 GeV

Blue lines: with 3rd or 5th harmonic energy spread reduction system
Black lines: without energy spread reduction

The energy spread reduction system is based on 3rd or 5th harmonic cavities

Longitudinal polarization profile along the bunch

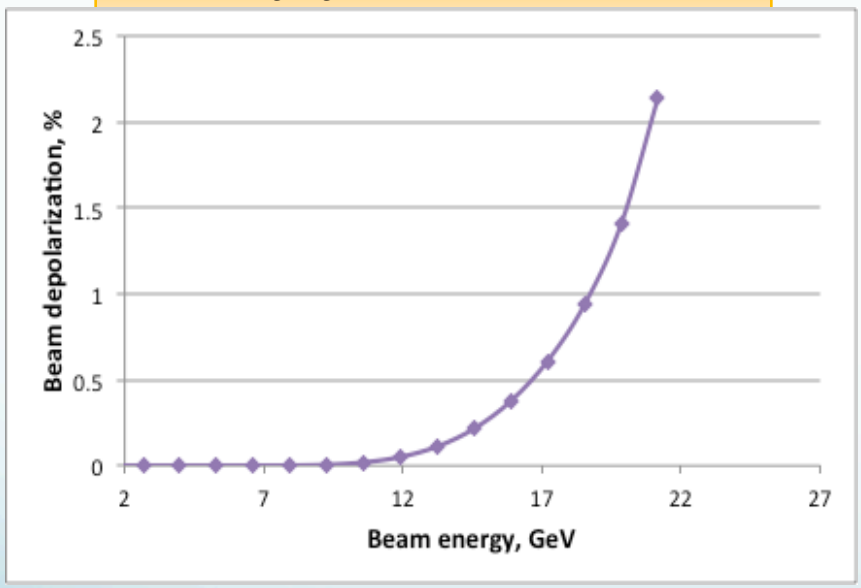


The energy spread created by the beam interaction with the beam pipe resistive wall and with the linac cavity wakes reduces spin de-coherence effect

Depolarization effects

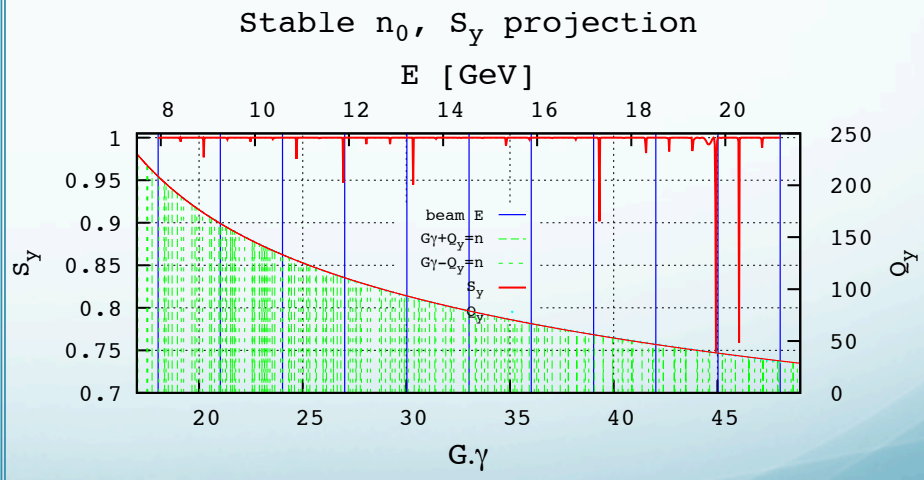
© F. Meot, V. Ptitsyn

Depolarization due to spin diffusion caused by synchrotron radiation



SLC experience:
the betatron motion in the arcs was in the resonance with the spin motion. Thus the polarization was sensitive to the vertical orbits

Lattice resonances



FFAG cell tunes can be choosen to avoid these resonances

Hadron-electron synchronization schemes

Main synchronization condition:
the electron and hadron bunch repetition frequencies at the collision points have to be the same:

$$f_{be} = f_{bh}$$

The hadron bunch frequency (at the fixed circumference) depends on the hadron energy

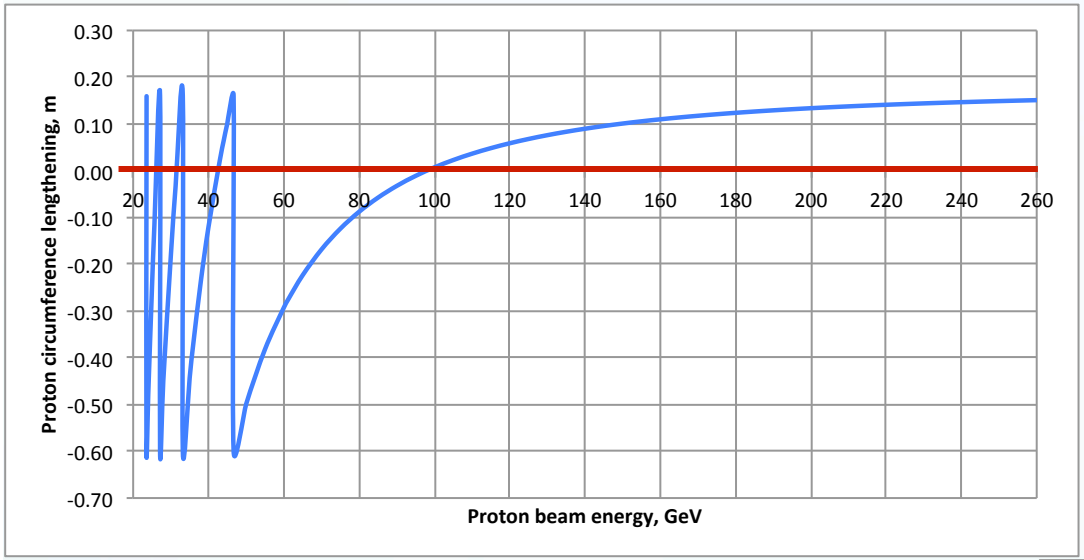
Presently accepted solution for the frequency synchronization includes:

- **Hadron delay line**
  Preliminary design provides up to 16 cm path lengthening ability.
  Movable warm magnets (up to 1 m).

- **The RF harmonic switching** method is assumed to operate with the hadron energies <50 Gev/n

Hadron circumference lengthening and harmonic switching

Hadron circumference lenghtening



$$C_e = \frac{h_e}{5280}\frac{C_h}{\beta_h}$$

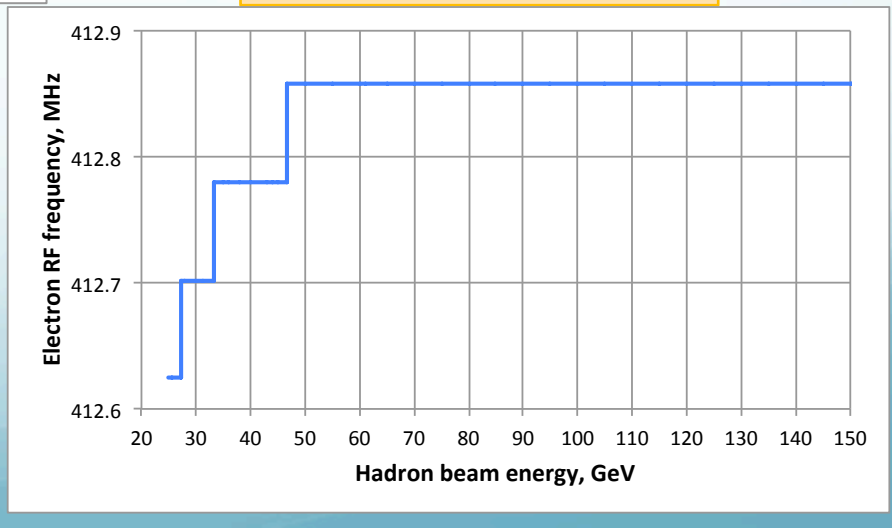
Assumes max 16cm delay line

The operation is possible only above the red line (positive path lengthening)

Sharp changes corresponds to the change of electron RF harmonic (h_e)

Accessible proton energy ranges:
100-250 GeV; 43-46 GeV; 31.6-33.2 GeV;
26.3-27.1 GeV; 23-23.5 GeV

Linac RF frequency



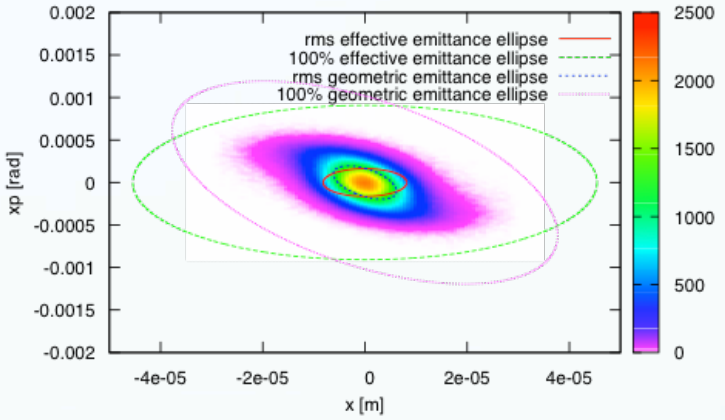
But, the harmonic switching modifies also the bunch patterns, which may become inappropriate (ions, linac transients)

Beam-Beam Effects in Linac-Ring Scheme

- e-beam disruption
  - *disruption parameter ~ 3-5*
  - *emittance increase by ~30%*
- Luminosity enhancement due to the electron beam pinching: *33%*
- Kink instability of hadron beam and its remedies

  from simulations: the feedback system (50-300 MHz) damps the instability
- Hadron beam heating by electron parameter noise

Electron beam distribution



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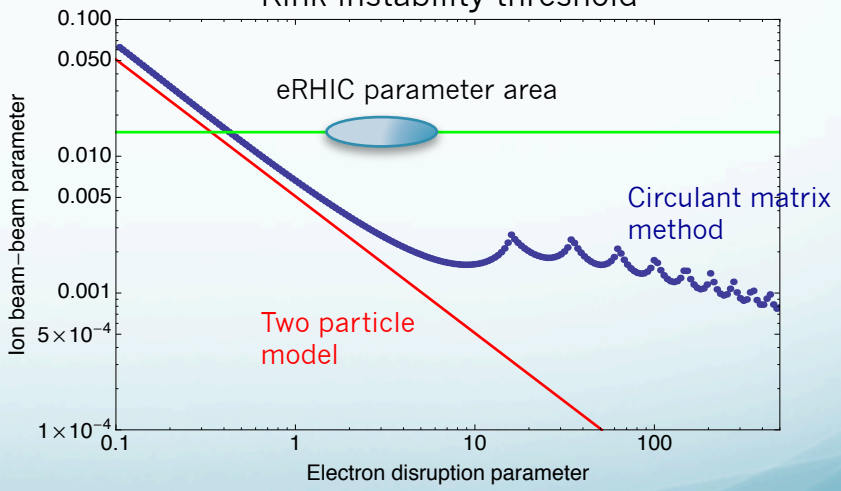
Kink instability threshold



Summary

- For the eRHIC FFAG design the lattice of most of accelerator components has been developed
- Base element of recirculation passes: bent FODO cell which employs permanent magnet quadrupoles
- 80% longitudinal polarization can be achieved with the energy spread reduction system
- Ion delay line and RF harmonic switching is used for hadron-electron frequency synchronization
- Major beam dynamics effects have been considered (beam-beam, multipass BBU, energy loss/spread due to impedances, beam-ion interactions ...)

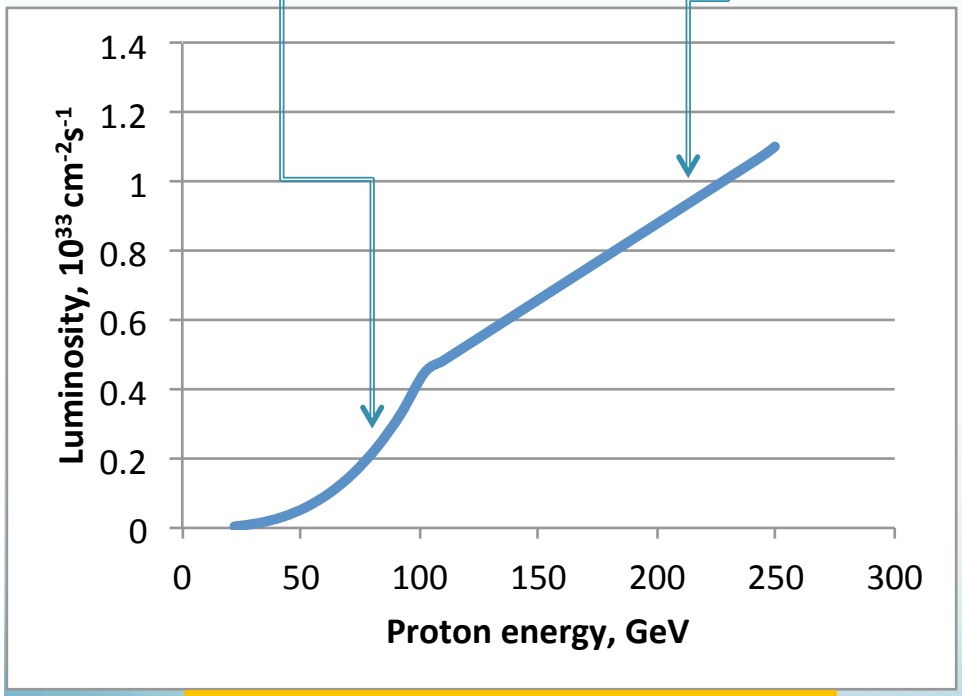
Backup slides

Luminosity energy dependence

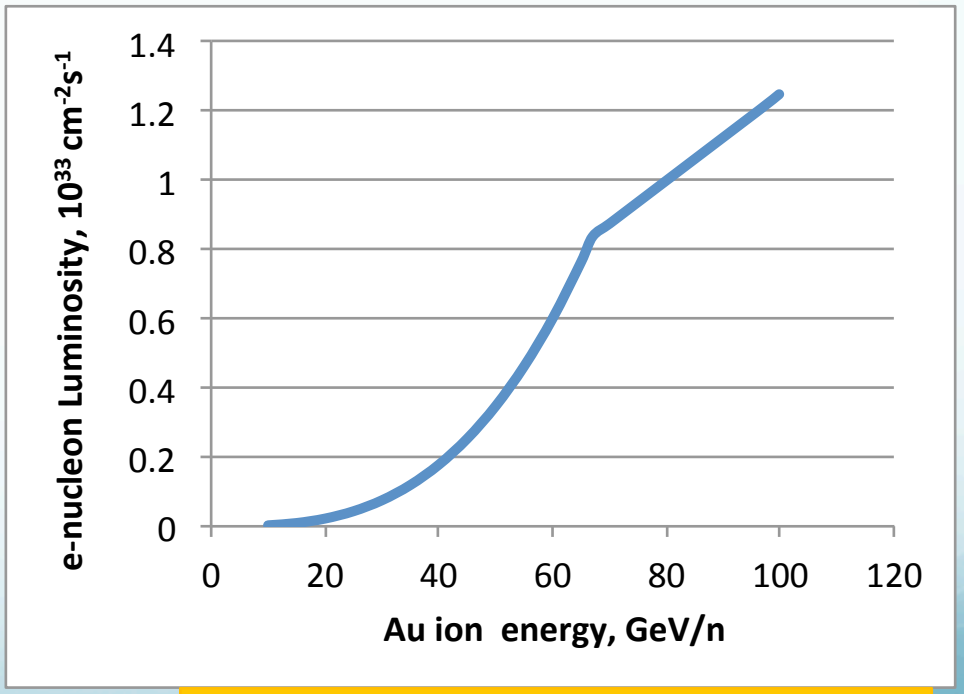
$$\Delta Q_{sp} \leq 0.035$$

Defined by space charge limit, reduced N_p

Defined by the beam-beam limit



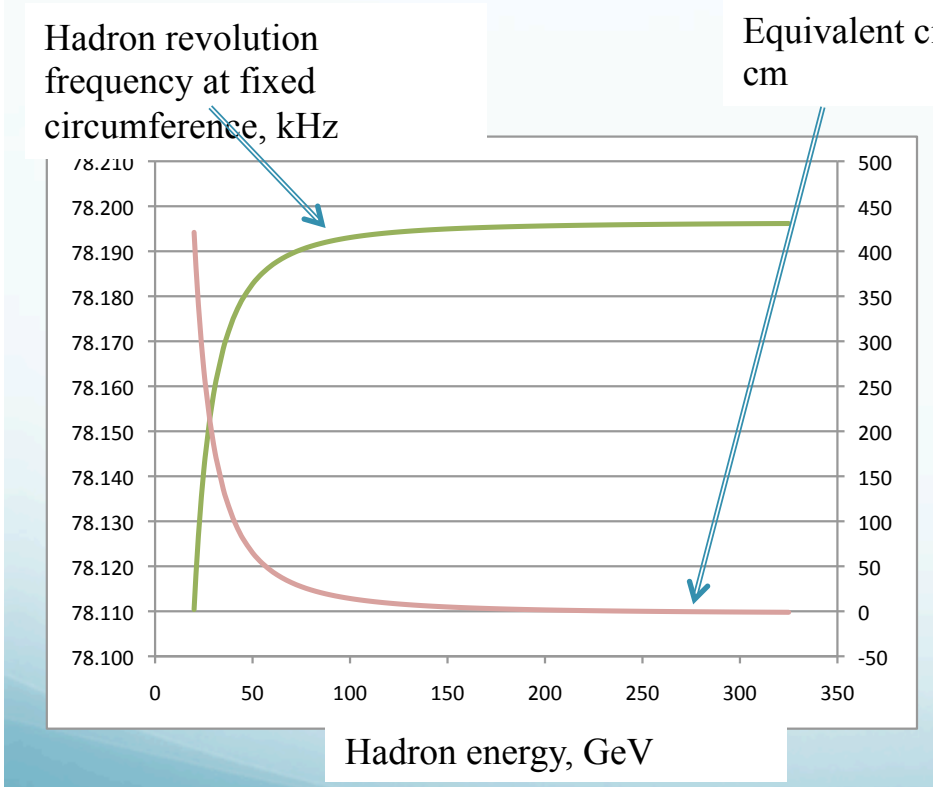
Electron-proton luminosity



Electron-Au nucleon luminosity

Electron-hadron beam synchronization

Main synchronization condition: the electron and hadron bunch frequencies at the collision points have to be the same: $f_{be} = f_{bh}$
But, the hadron bunch frequency (at the fixed circumference) depends on the hadron energy

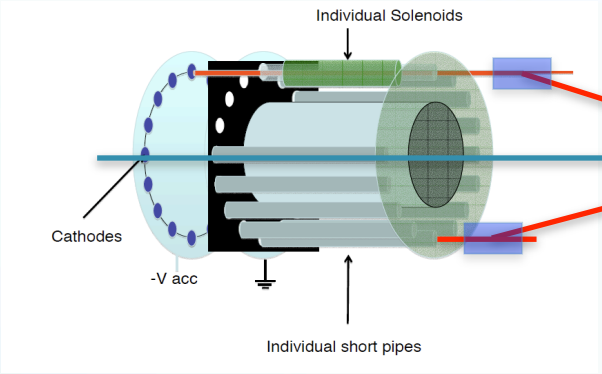


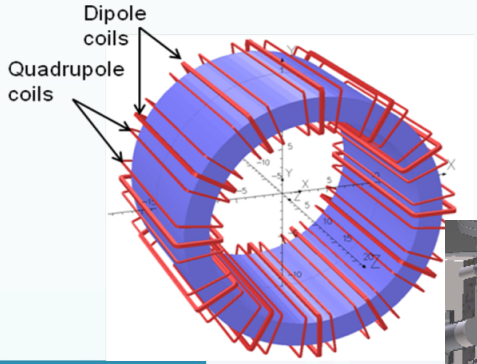
ΔC_e(250 GeV-50 GeV) ~ 65 cm

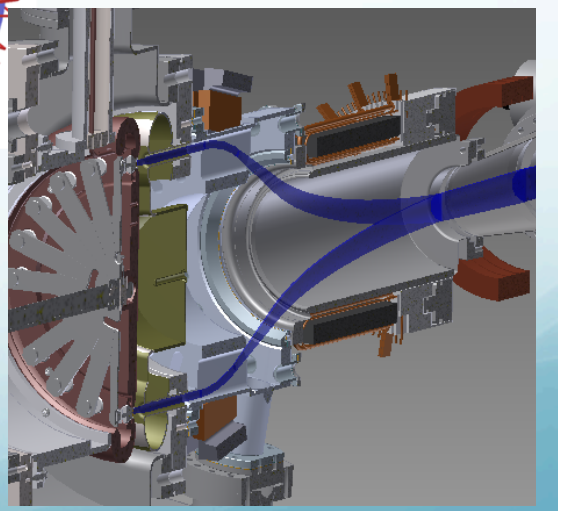
Electron bunch frequency has to match the hadron bunch frequency in wide energy range: 50-250 GeV/n

50 mA polarized electron source R&D

BNL Gatling Gun:
the current from multiple cathodes is merged: 20 cathodes, 2.5 mA each







- GG prototype is under construction
- First gun testing: end of 2014

Spin decoherence

$$\frac{d\left(\Delta\varphi_{sp}\right)}{d\theta} = A\Delta E\,; \qquad A = 2.27\frac{1}{GeV}$$

$$\Delta E = E - E(z=0)$$

- The energy spread in the beam causes the decoherence and the loss of beam polarization
- The eRHIC beam energy spread is dominated by the effect of the linac accelerator voltage waveform which introduces the quadratic dependence of the spin angle on the longitudinal coordinate of a particle
- Other important effects contributing to the energy spread: the beam interaction with the resistive wall and the cavity wakes, and the longitudinal motion errors (like R_{56} and path length errors)

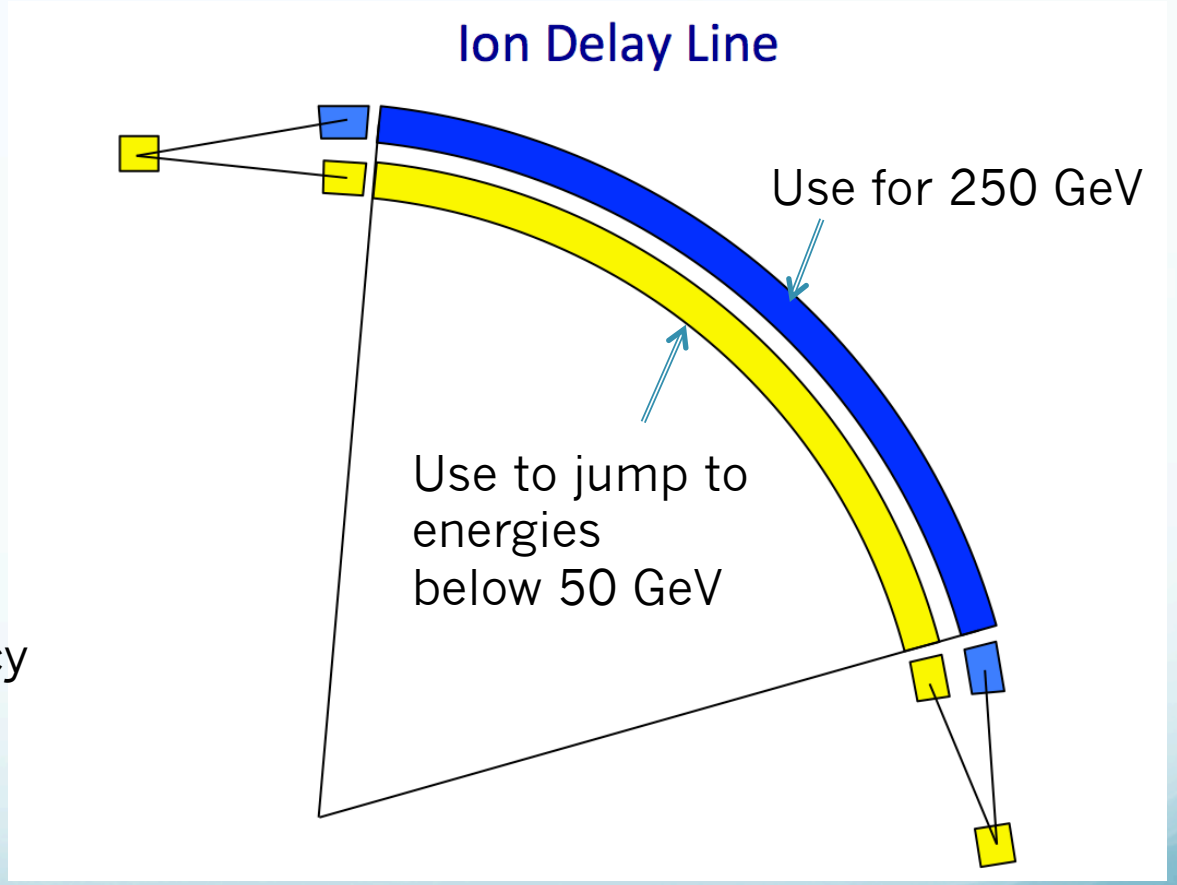
Possible alternative to the harmonic switching: sextant line switching

D.Trbojevic's proposal

Switch the hadron beam trajectory in one sextant between the present Blue and Yellow hadron lines

$\Delta L = 91$ cm

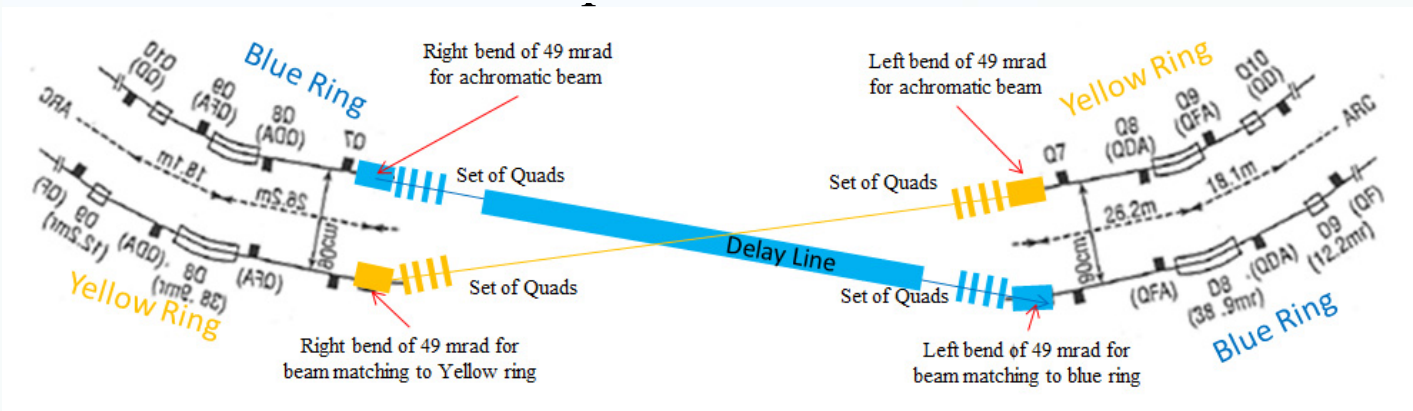
Preserves the beam pattern and the electron RF frequency

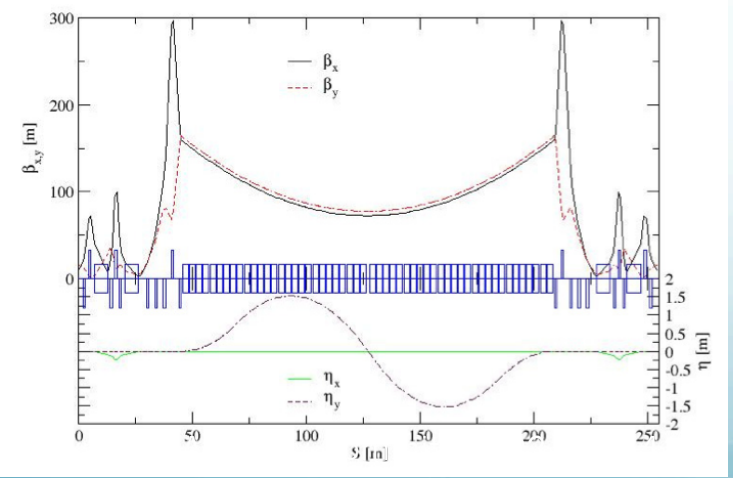


Ion Delay Line for RHIC

N.Tsoupas, et al., TUPFI079, IPAC'13

Up to 15 cm path length variation





It can be used for RHIC operation with asymmetric species, as well as for electron-hadron operation of future eRHIC.

Energy spread reduction parameters

	compensation using 3rd harmonic			compensation using 5th harmonic		
	to reach 80% pol. at 15.9 GeV	to reach 80% pol. at 21.2 GeV	for perfect spread compensation	to reach 80% pol. at 15.9 GeV	to reach 80% pol. at 21.2 GeV	for perfect spread compensation
E_c, GeV	-0.103	-0.130	-0.165	-0.034	-0.043	-0.055
E_m, GeV	1.425	1.452	1.487	1.356	1.365	1.377
$\Delta E_m/E_{m0}$, %	7.8	9.9	12.5	2.6	3.3	4.2

E_m is the main linac energy gain.
E_{m0} =1.322 GeV, the gain of the main linac without the compensation
E_c is the energy gain of the string of compensation cavities

Energy loss/spread summary

Top: 15.9 GeV
Bottom: 21.2 GeV

	CSR	Machine impedances	Wall roughness	Synchrotron Radiation	Total
Energy loss, MeV	Suppressed	12	Negligible	221	233
		6		540	546
Full energy spread, MeV	Suppressed	19	Negligible	2.8	20
		10		6.7	11
Power loss, MW	Suppressed	0.6	Negligible	11.05	11.65
		0.11		9.99	10.1